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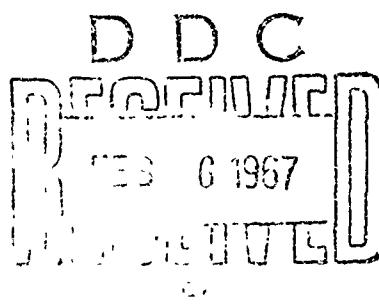
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**Design and Operation of the BSRL Pebble Bed  
Heater-Windtunnel Facility**

**Raymond P. Shreeve**

**J. K. Richmond**



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DESIGN AND OPERATION OF THE BSRL PEBBLE BED  
HEATER-WINDTUNNEL FACILITY

by

Raymond P. Shreeve and J. K. Richmond

October 1966

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1. INTRODUCTION

The BSRL pebble bed heater-windtunnel facility was designed with the primary object of providing a means of studying problems associated with combustion in supersonic flow. The need for basic research in this area was suggested in 1959 by J. K. Richmond while studying detonation waves using a shock tube [Ref. 1].

In order to be able to perform significant and realistic experiments in supersonic combustion certain minimum conditions were desired. These included that the test gas should be air, that the flow be supersonic and of minutes duration, that the static temperature be realistic and that the test section be of reasonable dimension. Such considerations led to the selection of a blowdown windtunnel using a storage heater. Power requirements precluded the use of continuous heating systems, although the use of arc heaters was also rejected on the grounds that a suitable arc heater was not likely to be available for some years. Also, it was thought desirable to avoid, as far as possible, facility development problems.

An appraisal of air heaters of the storage type [2] throughout the country, and the requirement that the BSRL facility should be put into operation with a minimum of delays, led to the selection of a pebble

bed heater using, for the present, alumina refractories. This type of heater will provide gas temperatures of up to 3,000°R. Higher gas temperatures could be obtained using zirconia (4,000°R), magnesia (4,500°R) or thoria (5,000°R), but none of these alternates were thought to have demonstrated a sufficient degree of reliability for immediate use. However, the pebble bed heater vessel was designed to allow the use of these higher temperature refractories if they became practical later on.

Having selected the type of heater necessary for experiments in supersonic combustion, the associated compressed air supply, the various pieces of hardware were designed to permit a range of future applications of the equipment. For example, two outlet flanges were provided on the pebble bed shell, of which one feeds the supersonic combustion tunnel and the other might later feed a hypersonic windtunnel. Also, the pebble bed pressure vessel was stressed for 1500 psi working pressure to allow high stagnation pressures (not necessary in the supersonic combustion tunnel), to be used in the hypersonic tunnel.

↓ This report will serve to describe the facility and to document the initial operating experience.

## 2. DESCRIPTION OF COMPONENTS

### a. General Arrangement

A block diagram showing the components of the facility is shown in Figure 1 and a floor plan is shown in Figure 2. The facility is located on the lower floor of the building at the east end. The heater vessel is supported in a pit outside the south-facing wall of the building and is positioned such that the two outlets feed windtunnels running north-south inside the laboratory. Three air compressors are mounted in a sound-proofed room in the extreme southwest corner of the laboratory feeding air storage vessels mounted outside the south-facing wall. A control room on the west side of the laboratory serves as the central control station for the complete facility.

### b. Compressed Air Supply

Three Worthington 4-stage, 50 HP air compressors each deliver 20 cubic feet per hour at a maximum pressure of 3,000 psi. The air is pumped through a Dollinger filter-separator (Model AHP-01) and a Van-Air desicant drier (Model 25-30) into receivers. The dew point of the stored air is - 40°F. Figure 3 shows a view of the compressor room, and the receivers, rated variously between 1200 and 1600 psi, can be seen in Figure 4.

### c. Pebble Bed Heater

(1) Design Considerations. The pebble bed heater is an accumulator in which heat from a long-duration, low-powered firing cycle is stored by a mass of refractory material and then removed during a short, high-powered blowdown cycle. A schematic of the heater is shown

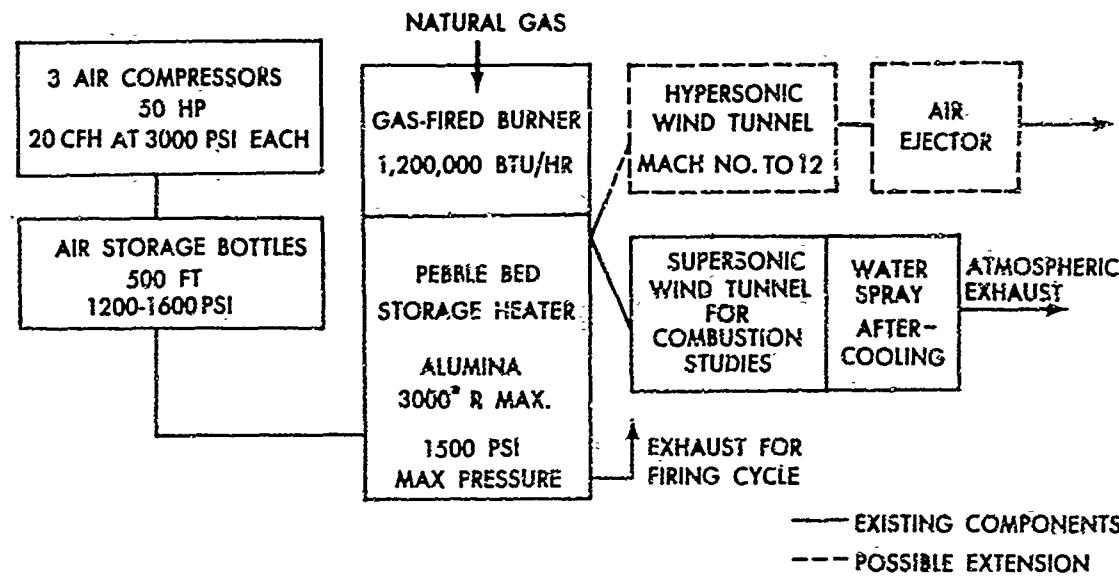


Fig. 1. Block diagram of the facility.

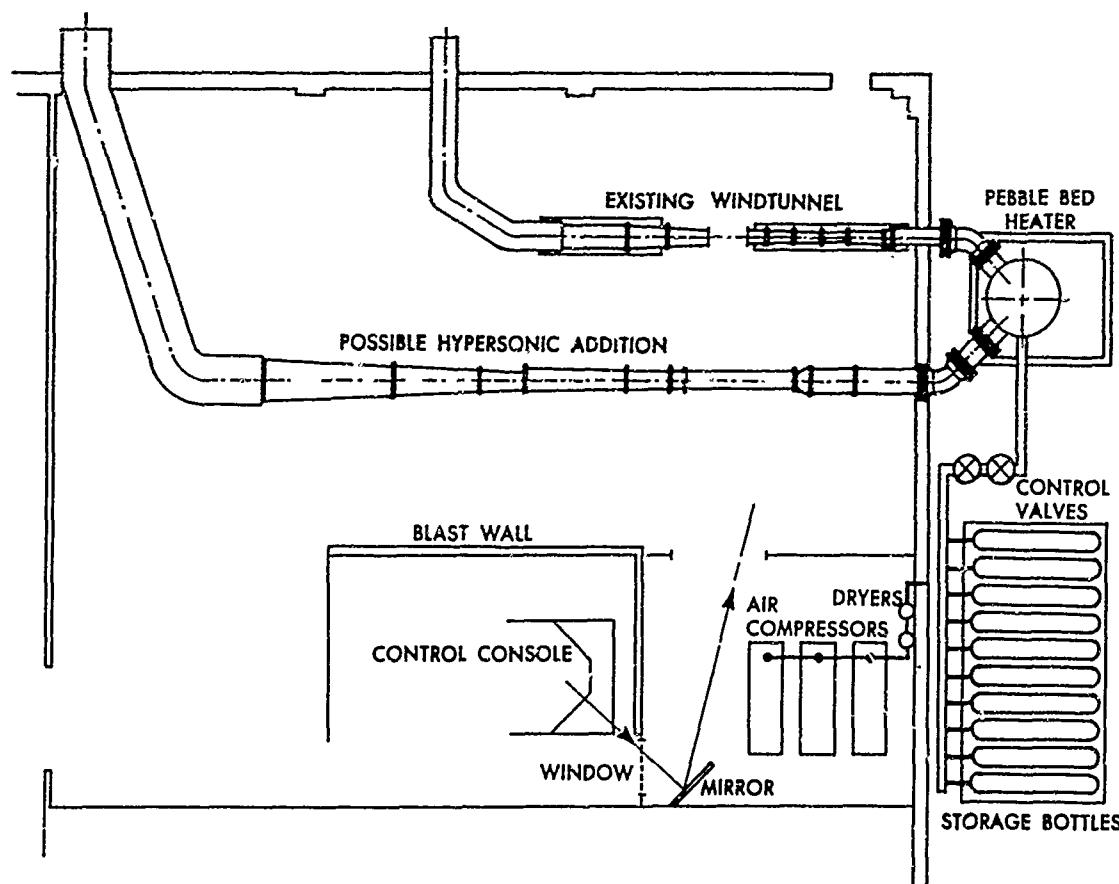


Fig. 2. Floor plan of the facility.

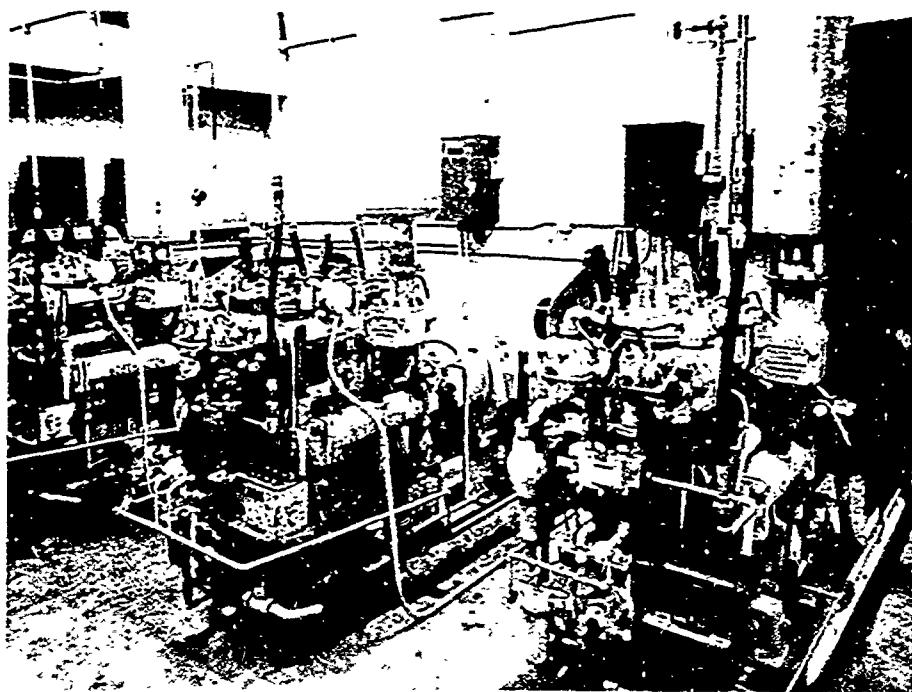


Fig. 3. View of the compressor room.

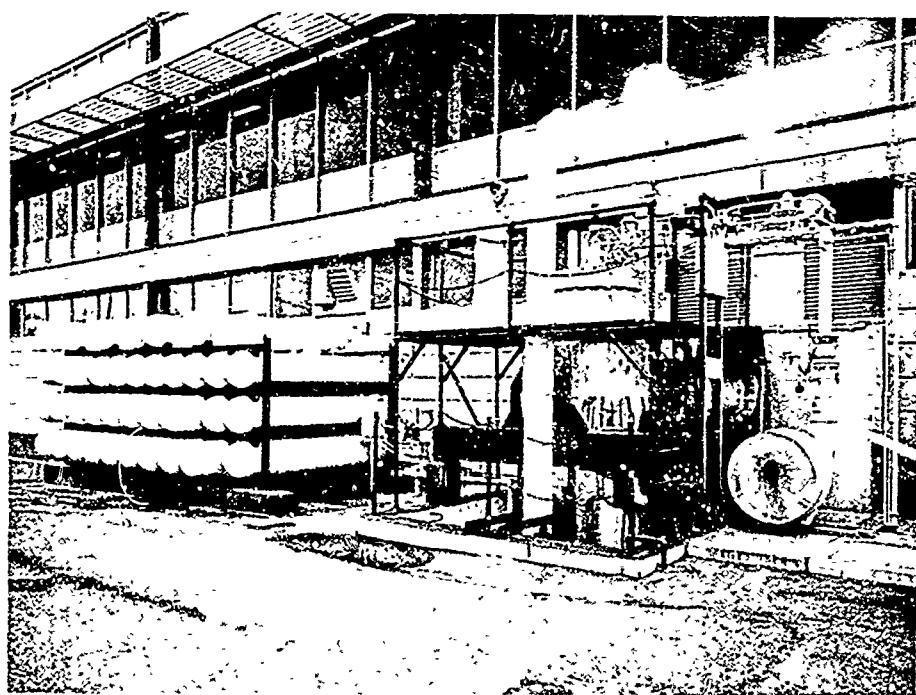


Fig. 4. View of the pebble bed heater and air storage bottles.

in Figure 5. The pebble bed consists of a volume (28" diameter by 9'6" high) of alumina pebbles, supported by a hastalloy metal grate and surrounded by assorted refractory materials 15" thick. The extreme 6" at either end consists of 1" diameter pebbles and the rest are nominally 3/8" diameter. The heater can be seen in Figure 4.

A natural gas burner supplying 1,200,000 Btu per hour is mounted in the top of the containing pressure vessel which is stressed for 1500 psi working pressure. During the firing cycle the burner forces a draft of hot air and combustion products down through the pebble bed and out through an exhaust stack at the bottom. Water-spray cooling is provided in the pipe leading from the bottom of the bed. To change from the firing to the blowdown cycle, the burner is shut off and isolated from the vessel by high pressure valves, the exhaust stack valve is closed and a diaphragm isolating the heater from the windtunnel is removed. The opening of a control valve in the high pressure air line then begins the windtunnel run. The air, introduced at the base of the pressure vessel, becomes heated on passing up through the bed and flows out through the windtunnel.

The heater was sized to satisfy the requirements of the supersonic windtunnel for combustion studies, for which the run time was to be of at least five minutes duration. A mass flow of 7 lbs/sec was designed for, with the normal operation expected at 2.5 lbs/sec.

Heat transfer and pressure drop calculations were made using methods similar to those of Reference 3 which follows the work of Bloom [Ref. 4]. From a comparison of the results for various sizes of pebbles and of lengths and diameter of bed, the dimensions shown in Figure 5

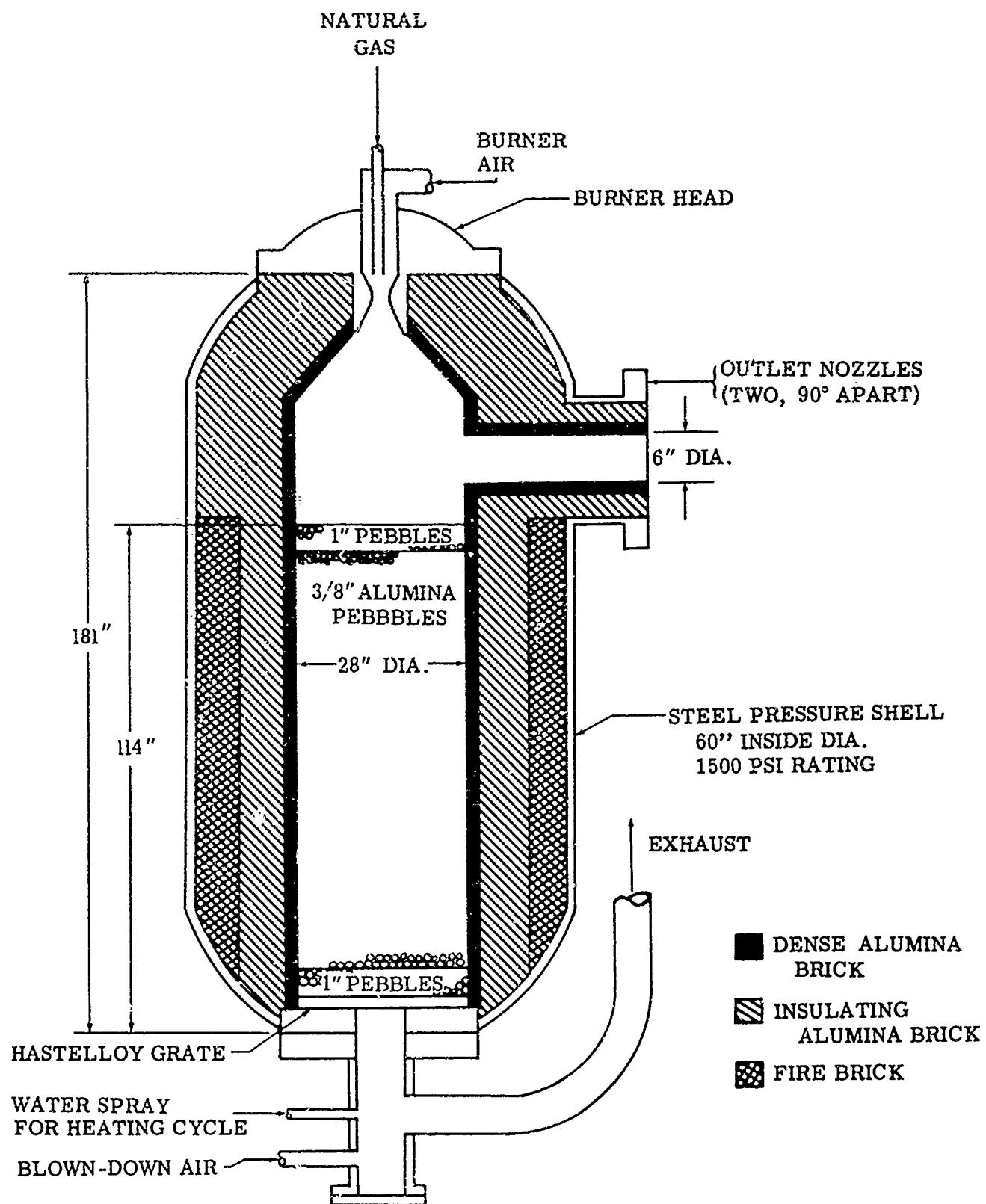


Fig. 5. Schematic of the pebble bed heater.

were selected. The selection of pebble size is a compromise between the superior heat transfer characteristics of small pebbles and the lower pressure drops through a bed of large pebbles. The pressure drop through the bed is important because of the condition of "lifting" which occurs when the pressure difference becomes large enough to overcome the weight of the pebbles. The calculated lifting conditions are shown in Figures 6 and 7 for the 3/8" and 1" pebbles, respectively, for several values of pebble temperature. To avoid lifting at a desired mass flow, it is necessary to operate the heater at a pressure *higher* than that given by the curves in Figure 6. It is then necessary that the mass flow versus pressure characteristic of the windtunnel nozzle lie everywhere above the lifting curve. The characteristic of the  $M = 4.5$  nozzle is also shown in Figure 6.

(2) Natural Gas Burner. A schematic of the natural gas burner, which was designed in-house, is shown in Figure 8. A 44 ounce blower supplies atmospheric air through a butterfly control valve to the burner, which is mounted in the top of the heater vessel. The burner receives natural gas from a 4" city main at 5 psig through a safety shutoff valve and interlocked regulator system. The burner head, shown in Figure 9, uses a central gas jet surrounded by eight air nozzles.

A premixed pilot flame is provided below the main burner which must be ignited (using a spark discharge) before the main gas safety valve can be reset. This safety interlock is provided using a Minneapolis-Honeywell ultraviolet flame detector in conjunction with a "Protecto Relay". The detector sights vertically downwards through the main gas jet.

During a blowdown cycle the air and gas lines to the burner are

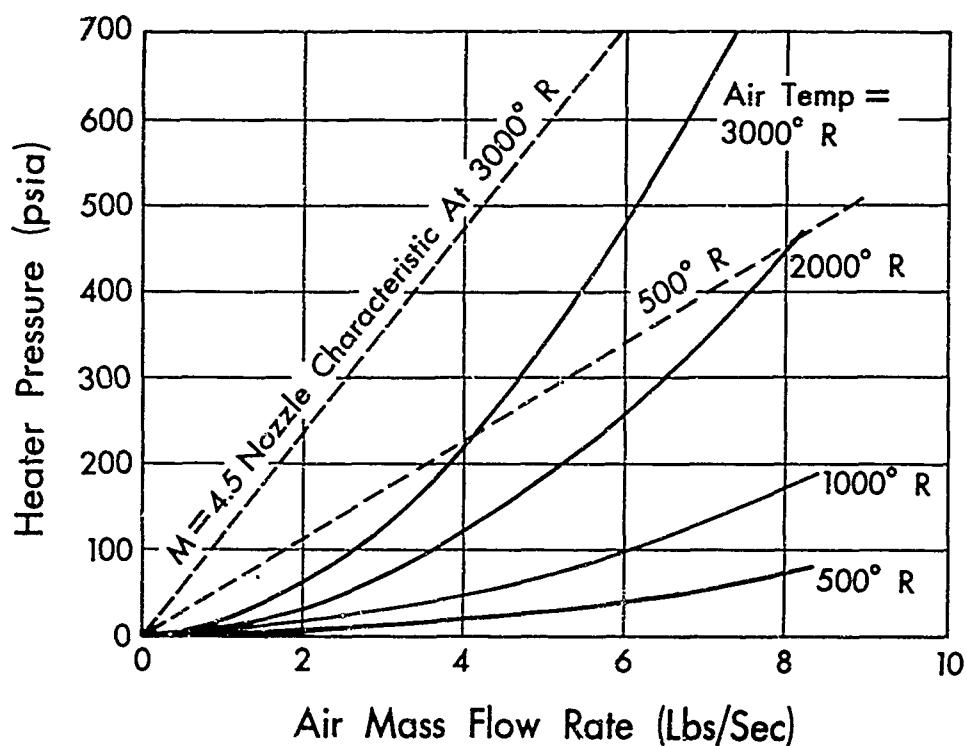


Fig. 6. Lifting limits for the pebble bed heater (3/8" pebbles).

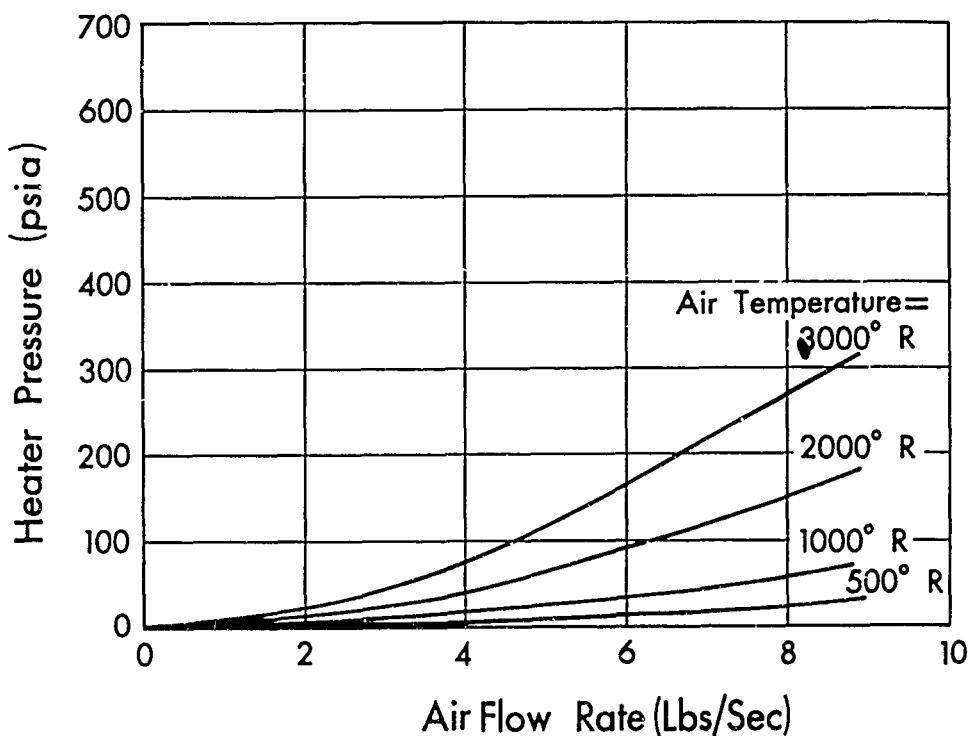


Fig. 7. Lifting limits for the pebble bed heater (1" pebbles).

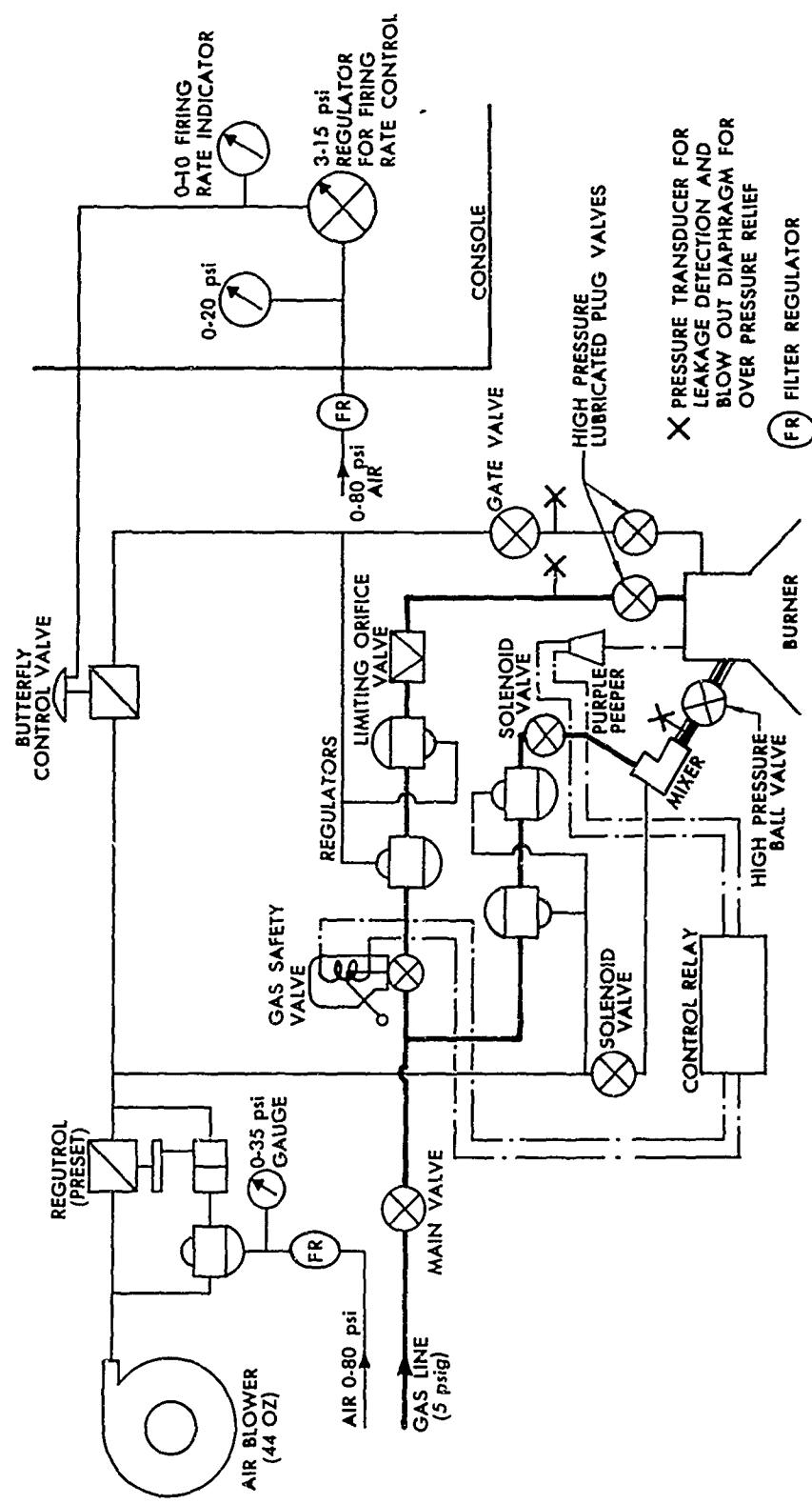


Fig. 8. Diagram of the natural gas burner.

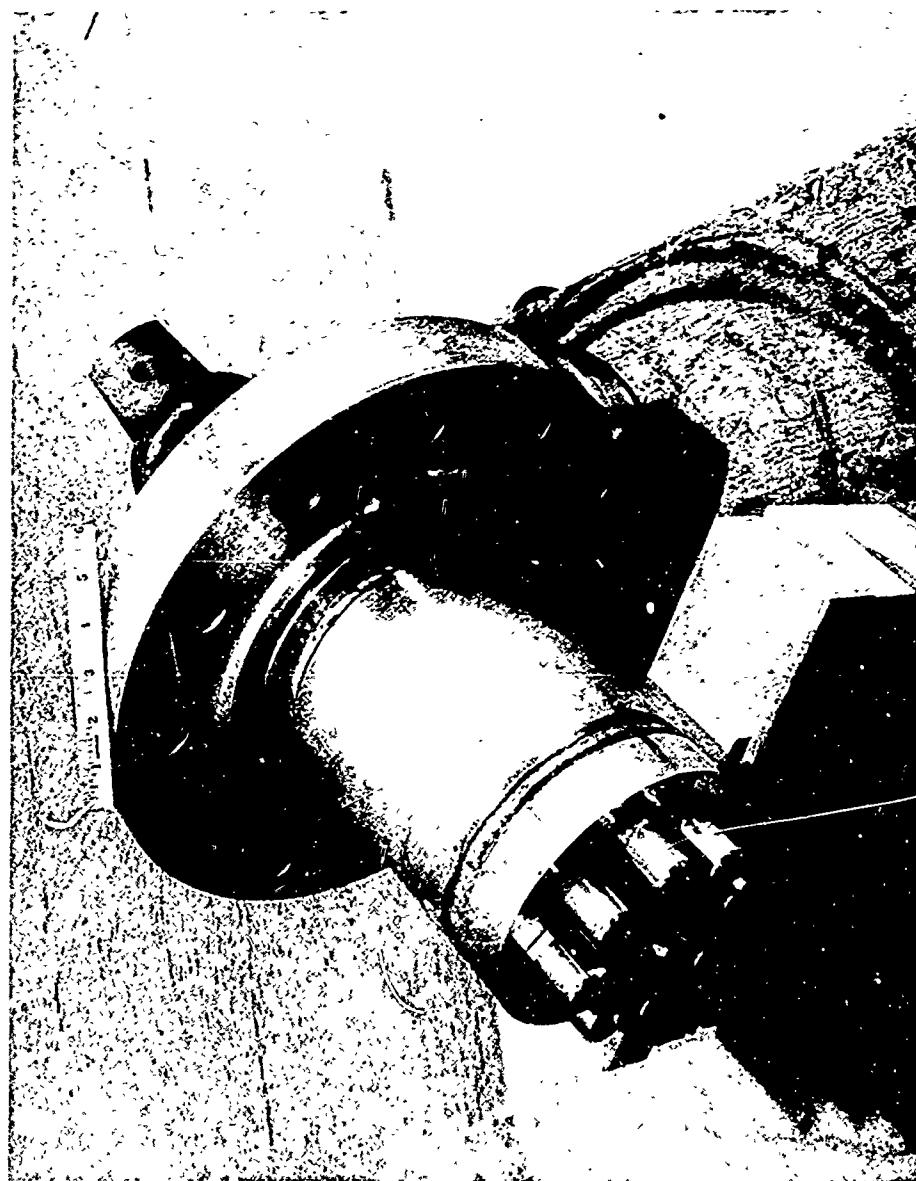


Fig. 9. View of the burner head.

closed by 4" and 2" lubricated-plug valves. The pilot assembly is isolated by a  $\frac{1}{2}$ " ball valve.

(3) Water-Cooled Grate. The alumina pebbles are supported by simple grate of straight hastelloy metal bars, 5/8" thick by 2" deep, which are set into the bottom flange of the pressure vessel with  $\frac{1}{2}$ " spacers. Two industrial fog nozzles spray cooling water up onto the grate bars during firing to maintain a grate temperature below 500°F. This water also cools the flue gases and prevents overheating of the stack valve and outlet piping. Excess water is drained from the bottom of the heater. All metal surfaces are maintained above 212°F to prevent water accumulation anywhere inside the vessel or piping. It was necessary to install a single aluminum radiation shield around the pressure vessel in order to achieve sufficiently high skin temperatures over the lower half.

(4) Temperature Instrumentation. Chromel-Alumel thermocouples are used to monitor surface temperatures of the pressure vessel of the grate bars and of the water-cooled stainless steel shelf which supports the insulating brick in the top arch of the vessel.

The temperature of the pebbles is measured in three locations. A platinum-platinum 13% rhodium thermocouple in an alumina protection tube rests on the top of the pebbles. Its reading gives the pebble temperature and, after a sufficiently long firing period at fixed burner condition, the firing temperature. Two Chromel-Alumel thermocouples in inconel protection tubes are inserted up through the grate bars, 6" and 12" into the pebbles. These indicated temperatures, in conjunction with the time and temperature of firing, are used to obtain the approximate

temperature profile at blowdown. Strip chart recording potentiometers are used to record these temperatures. [For the initial operation of the heater, a total of six thermocouples were distributed throughout the height of the pebble bed using feed-throughs at the base flange of the vessel. During the first few cycles of operation, the temperature-time histories were recorded for several firing conditions, before the four longest couples failed as a result of pebble movement. An attempt to improve on the installation was not successful and hence only the two shortest thermocouples are now used.]

A schematic of the temperature measuring instrumentation is shown in Figure 10.

d. Controls and Operation - Safety Features

Control of both firing and blowdown cycles of operation is directed from a single console whose location is shown in Figure 2. The console, designed for simplicity and safety of operation, uses a sequence of indicating lamps for each cycle of operation (Figure 11). For example, in going from firing to blowdown cycle, the operator must only check that one row of lights is totally on and the other totally off before opening the control valve. The change from blowdown to firing cycle (after the windtunnel has been disconnected from the heater) is made simply by throwing a row of switches arranged in order below the lights. The change-over between cycles takes less than three minutes.

In Figure 11, the left hand panel controls the firing cycle and the center one the blowdown. The right hand panel contains a window through which, using a large mirror, the windtunnel can be observed during operation. The walls dividing the control room from the windtunnel area

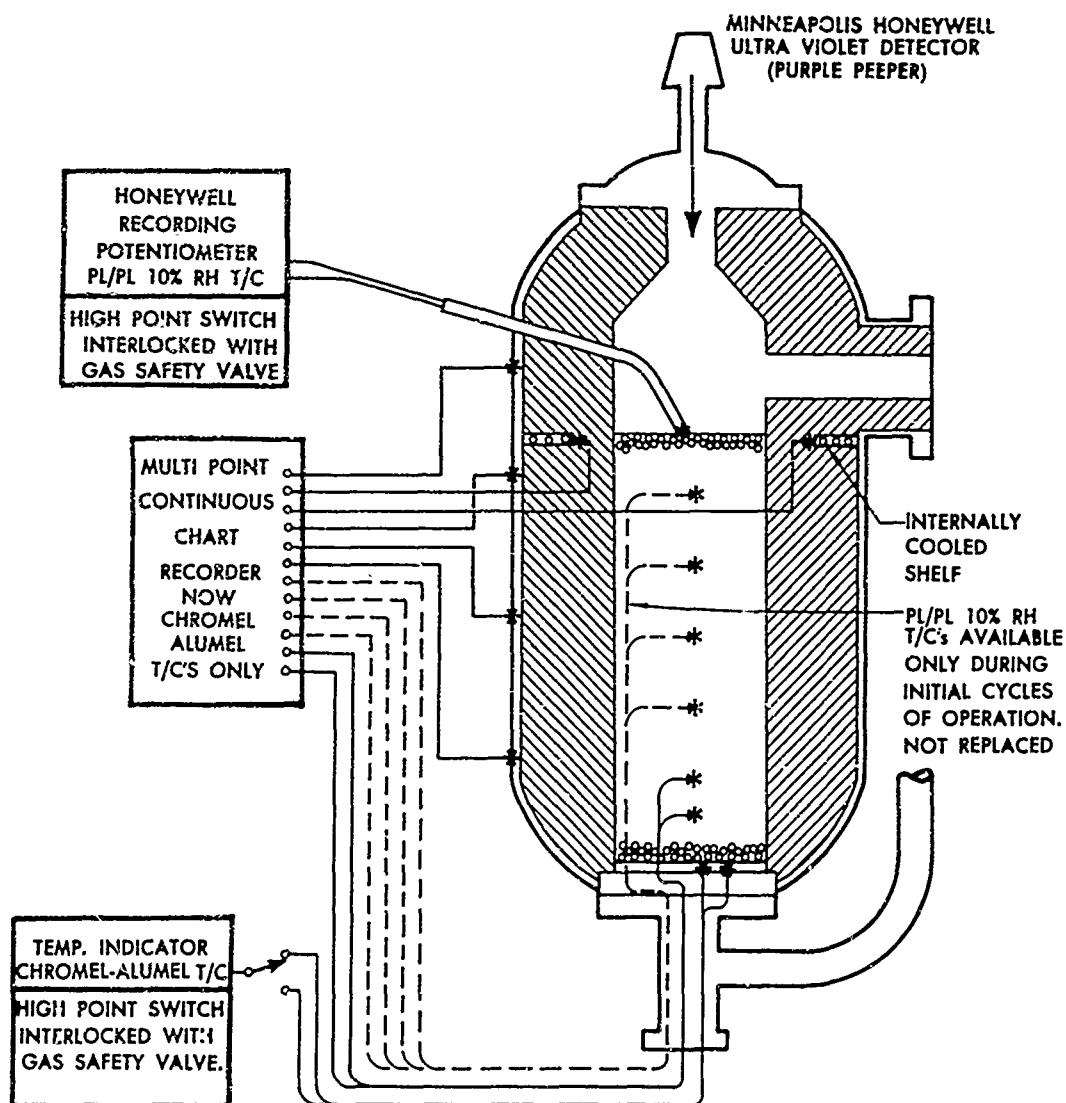


Fig. 10. Schematic of pebble bed temperature measuring equipment.

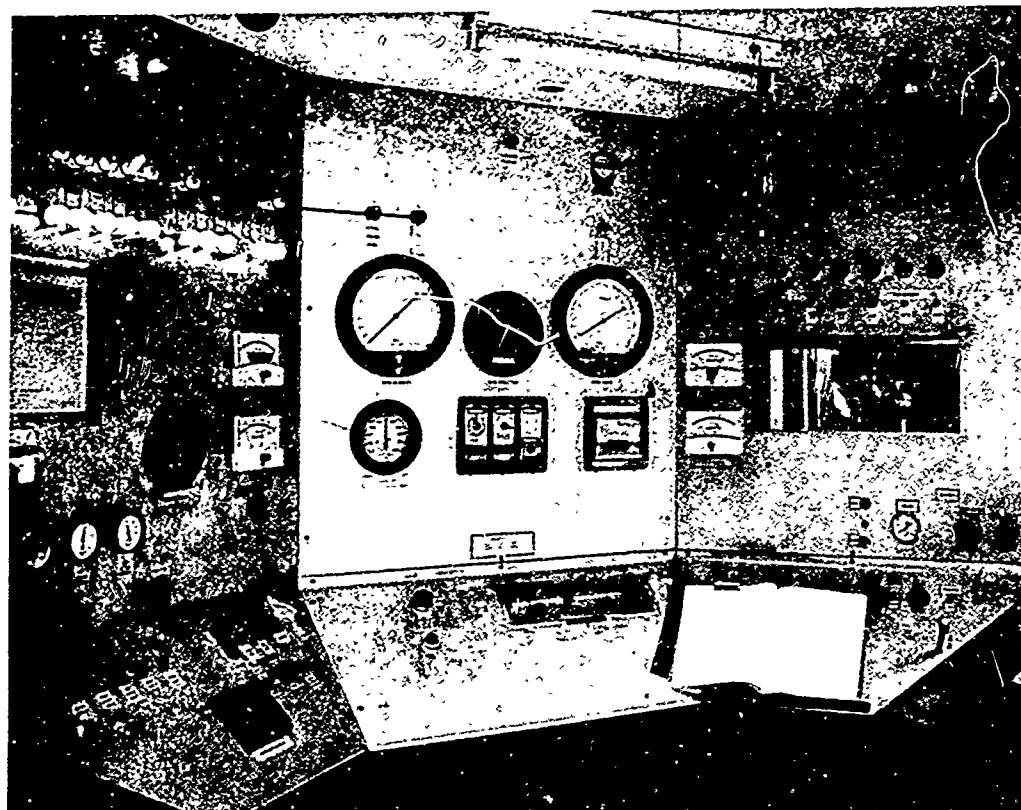


Fig. 11. View of the control console.

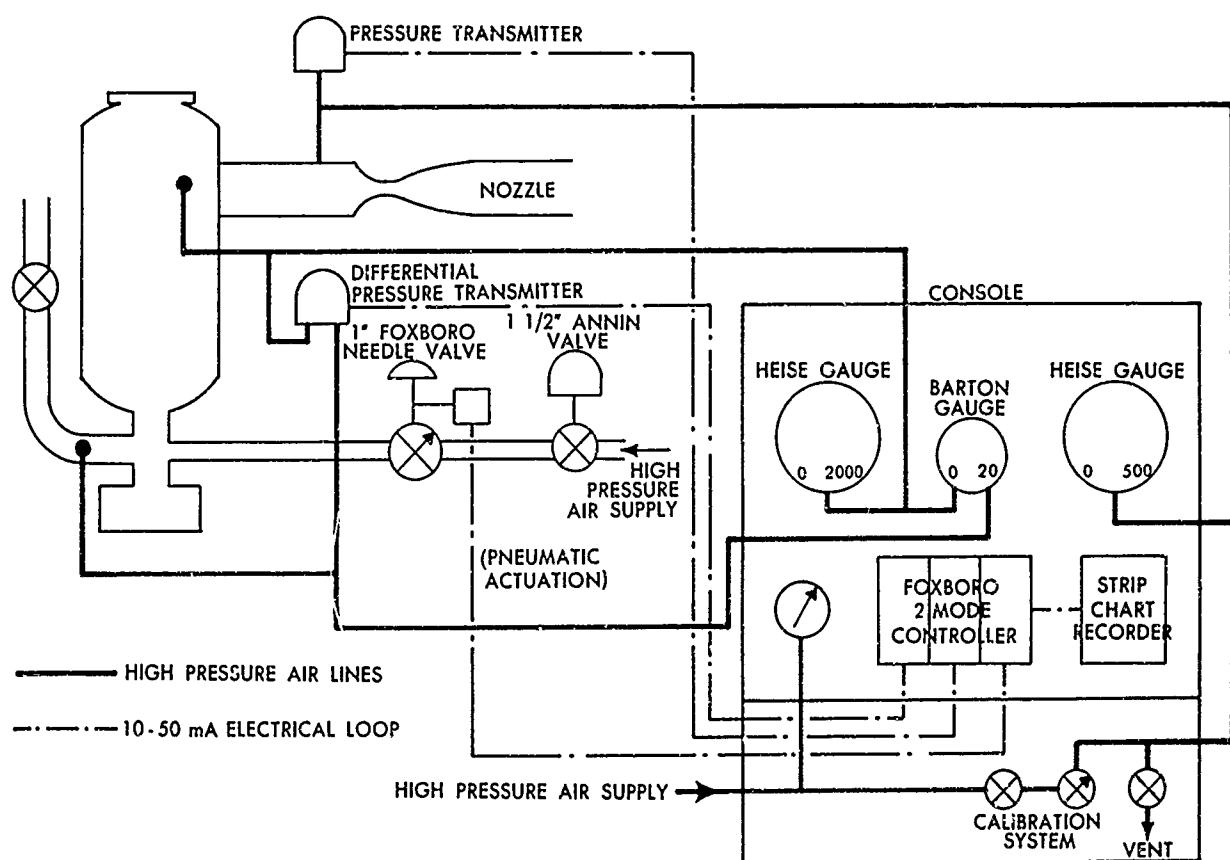


Fig. 12. Windtunnel pressure control system.

contain steel panels which would provide shrapnel protection in the event of an explosion.

#### Firing Cycle

Safety features have been included in the firing cycle controls which allow the burner to operate without attention. A fail-safe, manual-reset gas safety valve (Figure 8) will cut off the fuel to the burner if:

- (1) the flame detector indicates no flame,
- (2) the grate temperature exceeds a preset value, and
- (3) a float valve in the pit indicates failure of the sump pump which eliminates drained water from the pit.

Two minutes after the gas valve closes, a time delay relay shuts off the blower, which in turn shuts off the water spray to the grate. The time for which the gas safety valve is open is recorded by an electric timer, so that in the event of an automatic shutdown, the complete firing history is known.

#### Blowdown Cycle

The operating controls for the windtunnel are shown schematically in Figure 12. An electric two-mode controller is used with a pneumatically actuated control valve to provide automatic startup and control of plenum pressure. The two modes are necessary since the controlled pressure must be achieved in such a way that the pebble lifting limit is at no time exceeded. The controller receives signals from both a transmitter sensing the plenum pressure and from a differential pressure transmitter sensing the pressure drop through the bed. The controller then controls the plenum pressure at its set point so long as the set

value of the pressure drop is not exceeded. The electric control loop uses standard Foxboro process control components with adjustable proportional band and reset rates. Two control valves are used, since different sizes were necessary for the Mach 2.5 and 4.5 windtunnel nozzles. The Mach 2.5 nozzle uses a 2" P. K. Paul valve with a Bonshaft and Fuchs cylinder actuator and Foxboro pneumatic power positioner. The Mach 4.5 nozzle used a 1" Foxboro needle valve with diaphragm actuator and electric positioner.

The blowdown procedure is as follows: the windtunnel is connected to the outlet flange of the heater and the cooling water main valve to the tunnel is opened. The row of panel lights must indicate that all high pressure block valves, including the 6" Cameron plug valve in the exhaust stack, are fully closed. The required plenum pressure is set at the controller, and with the differential pressure set point below zero the control is switched to automatic. The control valve remains closed. A 1½" Annin valve in the compressed air line is then opened and the differential pressure set point increased to 4 psi. The control valve opens and the desired set point is attained within 45 seconds.

Safety features active in the blowdown cycle include pressure switches sensing leakage of the high pressure block valves which isolate the burner lines and thermocouple switches which indicate overheating of the windtunnel nozzle blocks. An adverse condition triggers the automatic closing of the Annin valve. Blowout diaphragms are present to protect the burner lines in the event of a large leak at the block valves. Warning lights at the console indicate the triggering of these safety switches.

e. Supersonic Combustion Windtunnei

(1) Design Considerations. This windtunnel has components typical of supersonic blowdown windtunnels -- plenum, nozzle test section and diffuser. However, its intended use for combustion experiments gives rise to several unusual features. The requirement of high static temperatures and densities at supersonic Mach numbers results in high heat transfer rates to the walls. At the nozzle throat this rate exceeds 1000 Btu/ft<sup>2</sup> sec. All sections upstream of the diffuser are water-jacketed, and water spray injection at a possible rate of 60 gals/min is provided in the diffuser sections to both inert and cool the gases leaving the test region. A view of the windtunnel is shown in Figure 13.

(2) Plenum Chamber. The Mach 2.5 nozzle requires mass flow rates (2.5 - 7.5 lbs/sec) which exceed the pebble bed lifting limit at the desired stagnation pressure (30 - 90 psia). Consequently, a 1" diameter orifice is provided between the heater and the plenum chamber which allows the heater to operate at higher pressures (300 - 900 psia). The arrangement of this plenum is shown in Figure 14. Provision has been made for the possible addition of hydrogen gas into the air stream in order to raise the stagnation temperature from 3,000°R to 4,000°R, at the penalty of 10% H<sub>2</sub>O contamination.

The Mach 4.5 nozzle plenum chamber consists only of the two sections immediately upstream of the bellmouth in Figure 14, since this nozzle operates within the pebble bed heater lifting limit (2.4 lbs/sec at 350 psi) and therefore does not require the orifice.

(3) Nozzles. Both nozzles are two-dimensional with a constant width of 4". They consist of water-cooled copper machined blocks and

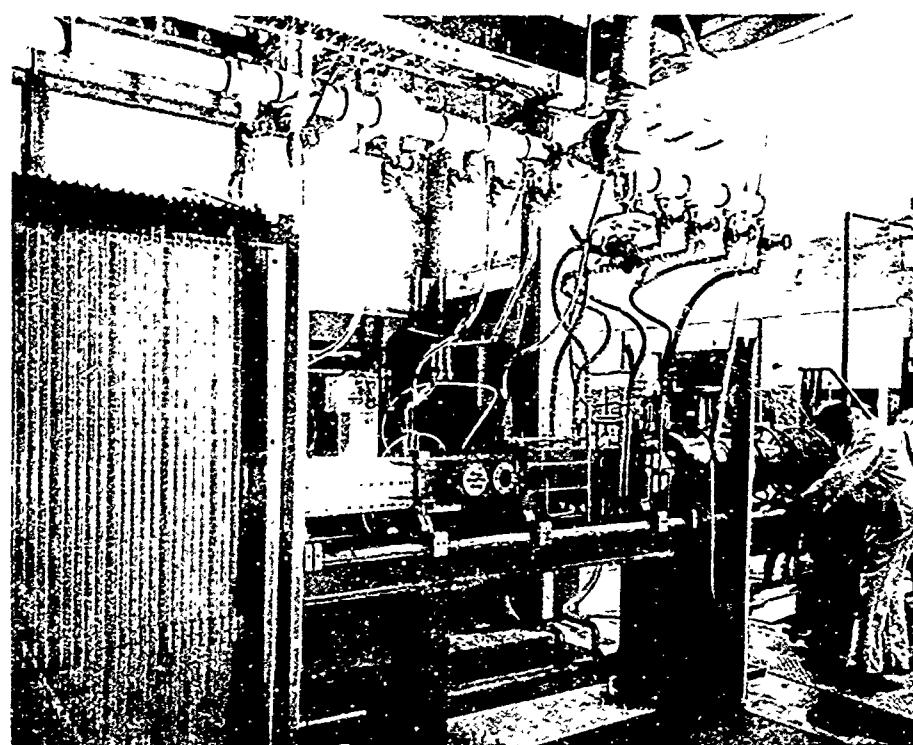


Fig. 13. View of the supersonic combustion windtunnel.

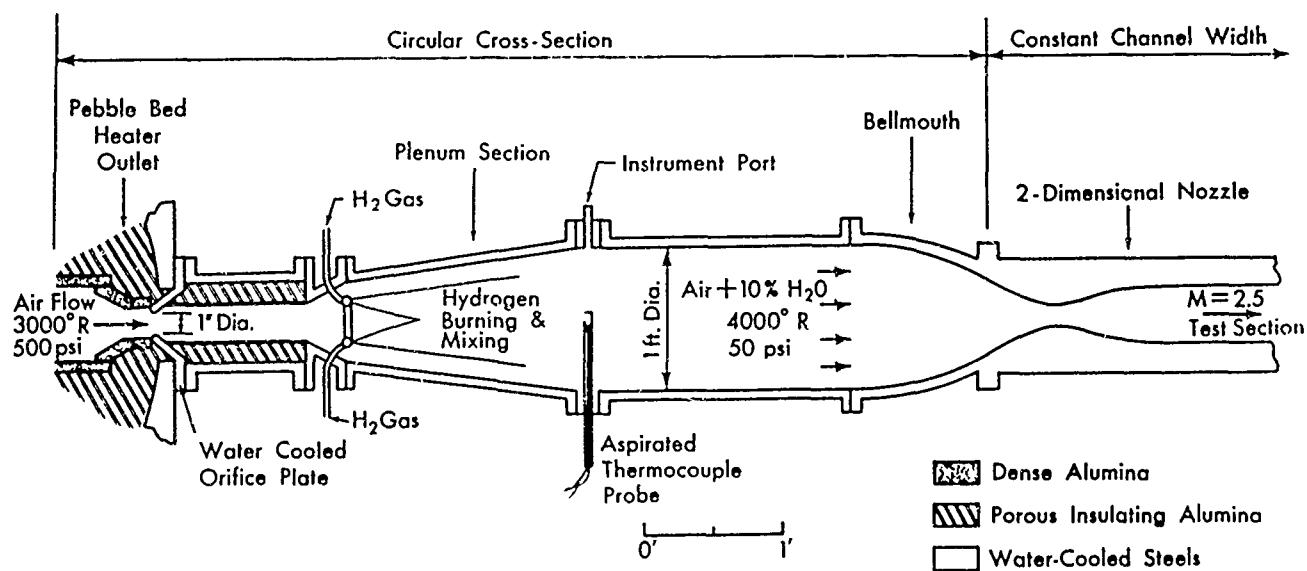


Fig. 14. Supersonic combustion windtunnel plenum chamber.

sidewall plates clamped together between sections of uncooled steel tank plate. Copper gaskets seal the nozzle between the bellmouth and the test section.

The contour of the  $M = 2.5$  nozzle was computed according to Reference 5 using the boundary layer correction suggested by Ruptash [6]. The throat height is 2.08" and the exit height is 6.00". The  $M = 4.5$  nozzle was designed using computer programs for equilibrium real gas flows which became available after the 2.5 nozzle was completed. Reference 7 was used for the inviscid computation and Reference 8 for the boundary layer calculation. In both nozzles the contoured wall was also adjusted to take account of the boundary layer displacement thickness on the sidewalls. The  $M = 4.5$  nozzle throat height is 0.205" and the exit height is 5.15". Three 1" diameter ports provide a choice of axial location for an aerofoil-shaped hydrogen injector to be used in the first combustion experiment.

Both nozzles have static pressure taps at 2" intervals in the contoured walls, and Chromel-Alumel thermocouples are imbedded in the copper at the throat station.

(4) Test Section. The test section is a duct 6 feet long with a 4" constant cross section and slowly diverging upper and lower walls. It is in three pieces, each 24" long, and mates smoothly with the  $M = 2.5$  nozzle. With the  $M = 4.5$  nozzle the flow into the test section is as a free jet. Static pressure taps are provided in the sidewalls at 2" intervals and small ports in the top and bottom walls allow the insertion of probes. On either side of the first test section are provided two 4" diameter ports which can be used to mount quartz windows or a

traversing probe mechanism. Figure 15 shows this section with windows in place and a probe held by a three-way traversing mechanism.

(5) Diffuser. No second throat diffuser is provided since the requirements for various combustion experiments will vary. The flow from the test section slowly diverges into a 21" diameter exhaust pipe. In the diverging section, an annular and axial water-spray system is used to cool and inert the flow.

f. Instrumentation

(1) Pressure. Static pressures are displayed on a fifty tube, 60" mercury manometer which has five individual reservoirs. If needed, the pressures are photographically recorded, simultaneously with the plenum chamber pressure which is displayed on a 16" Heise gauge. Impact pressures can be displayed on the manometer or directly recorded using a Moseley X-Y recorder with strain gauge transducers. Impact pressures range from 0 to 1 atmosphere gauge, and static pressures from 0 to 1 atmosphere absolute. On the console are indicated the pebble bed pressure, the plenum pressure (Heise gauges), and differential pressure across the pebbles (Barton gauge). A time history of the plenum pressure is obtained on a small Foxboro strip chart recorder.

(2) Temperature. A Minneapolis-Honeywell strip chart recorder is used with switching to record P1/P1Rh thermocouple outputs from an aspirated probe in the plenum, and from a thermocouple in contact with the top of the pebble bed. The plenum probe is an Aero-Research platinum shielded probe modified to improve its durability.

Cooling-water outlet temperatures are measured by Chromel-Alumel thermocouples and are displayed on a panel of small indicators.

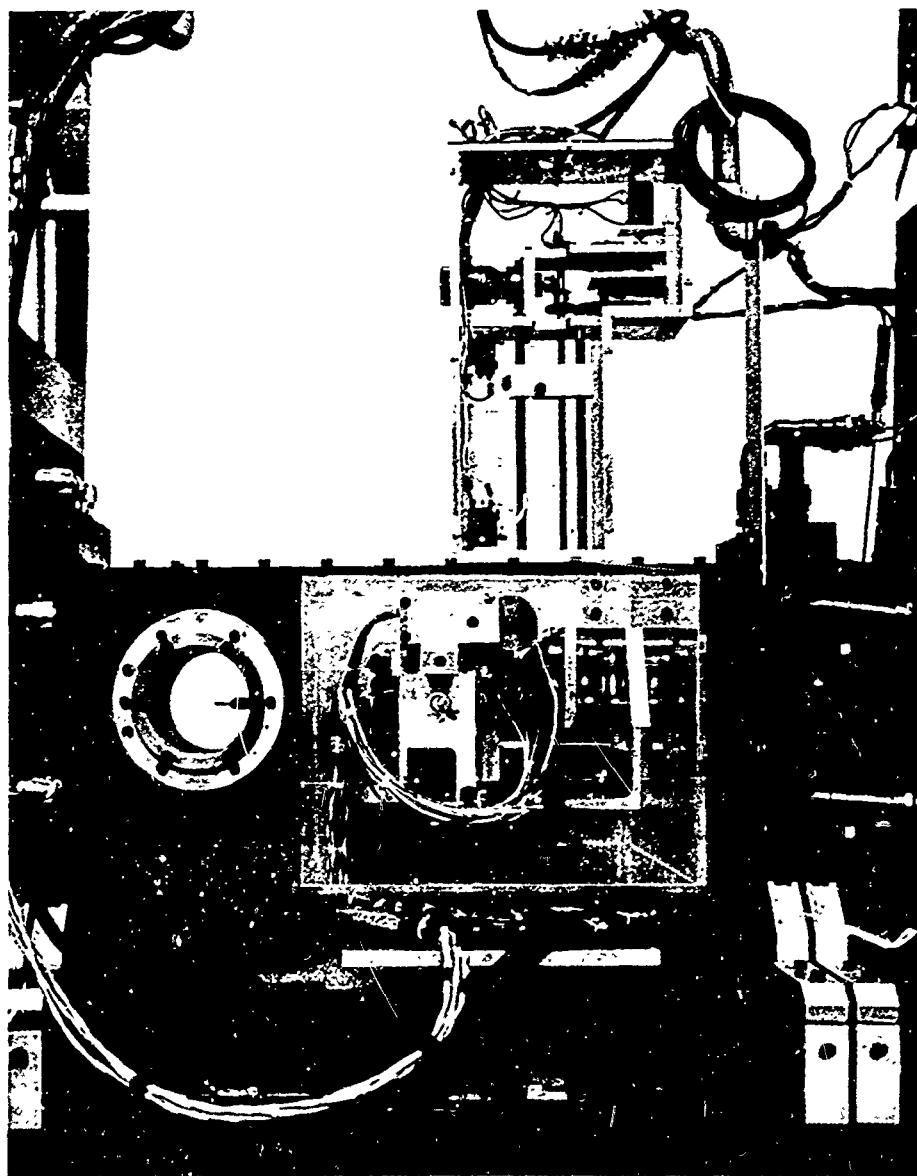


Fig. 15. View of the test section showing probe traversing mechanism.

A total of 24 indicators are used for the large number of separate water jackets.

(3) Gas Composition. The combustion experiments require gas sampling from the stream and subsequent analysis. Two analyzers are available. A Leeds and Northrup hydrogen analyzer using a thermal conductivity cell has the two ranges 0 - 5% and 0 - 30% with strip chart readout. A Beckman oxygen analyzer has one range, 0 - 20%, with a similar chart record.

(4) Schlieren Apparatus. A 4" single pass schlieren system uses a P.E.K. 150 watt continuous xenon arc lamp or a 10 Kvolt short duration spark source. 3" x 5" plates or strip polaroid film are used.

(5) Traversing Monochromator. Two continuously adjustable optical monochromators are mounted on a motor-driven table and can be used to survey across the test section window. Two Moseley X-Y plotters record the intensity of the selected wavelength versus position as the table is moved.

(6) Dew Point. A Cambridge Systems, Inc. Dewpointer (Model 992-C1) is used to monitor the dew point of the tunnel air during a test. The sample is taken from air drawn through the plenum stagnation temperature probe.

### 3. INITIAL OPERATING EXPERIENCE

#### a. Pebble Bed Heater

(1) Burner Calibration. The gas/air mixture ratio controls the firing temperature of the burner. For a fixed gas orifice setting (Figure 8) this ratio is held approximately constant by the gas regulator valves. The burner calibration consisted of determining the firing temperature for various settings of the limiting orifice while the firing rate was held constant. The firing rate is controlled by a motorized butterfly valve in the air line. The firing temperature is taken to be the equilibrium temperature measured by a shielded platinum-platinum rhodium thermocouple imbedded in the top layer of pebbles after more than 12 hours at the same firing rate and orifice setting.

The resulting calibration is shown in Figure 16. Using this calibration it is possible to reproduce tunnel stagnation temperature to better than 20°F. Figure 16 also shows the results of flue gas analysis for CO<sub>2</sub> content.

The burner has performed reliably and repeatably for more than 10,000 hours. The only source of trouble has been the sensing of the pilot flame by the ultraviolet detector. It was found necessary to keep the fitting around the sight glass heated, using heating tape, to prevent condensation on the 3/4" diameter window, and to use coaxial signal leads from the sensor to the protectorelay.

(2) Temperature Measurements. At the beginning of a wind-tunnel run the temperature distribution in the pebble bed should be flat over the upper several feet in order to ensure a constant stagnation temperature during the run. Temperature records obtained during the

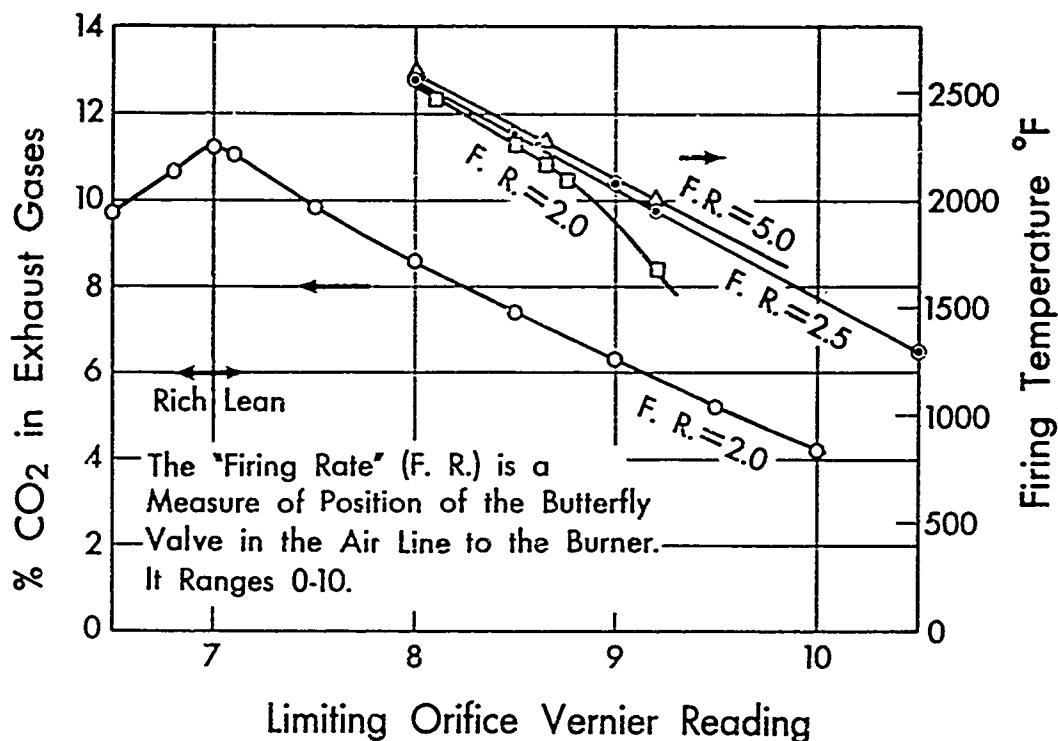


Fig. 16. Calibration of the natural gas burner.

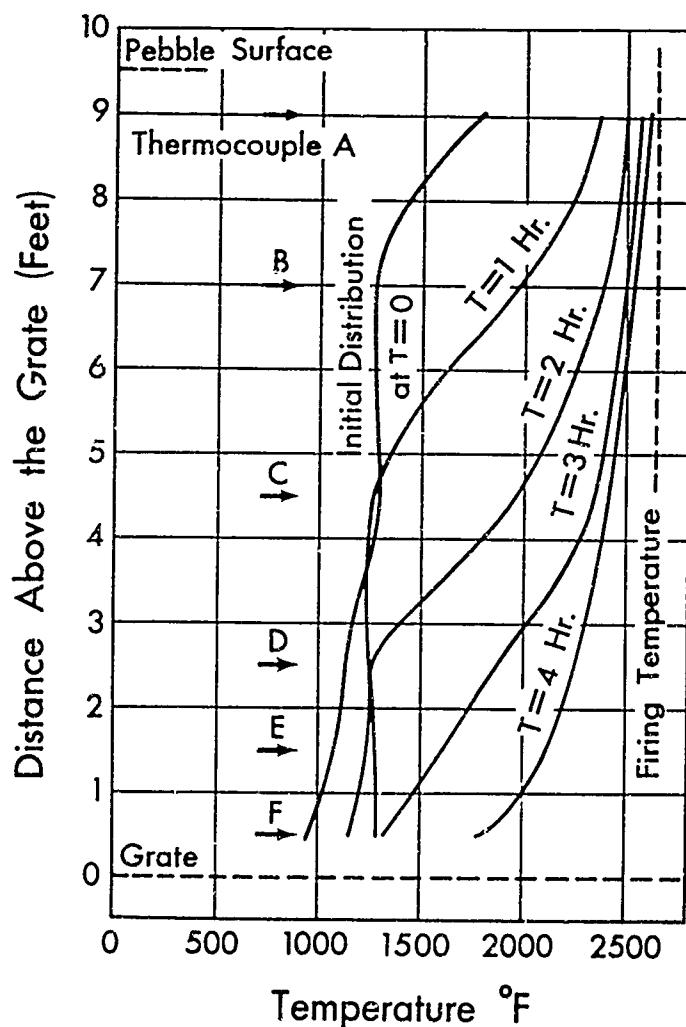


Fig. 17. Measured temperature distributions during a firing cycle (F.R. = 5.0).

early firing cycles, an example of which is shown in Figure 17, illustrate the difficulty of achieving this end. It is seen that the pebbles asymptotically approach a final temperature (the firing temperature) at a rate governed by the firing rate. A simple representation of the time necessary to achieve the desired temperature profile is not possible since it depends upon the initial temperature profile, which can be arbitrary.

Hence, using the experience contained in histories similar to Figure 17, a procedure was adopted of using overnight firing cycles at fairly low firing rates in preparation for tests at a single temperature during the day.

After the first test the heater can be refired at a high firing rate, using the calibration curves in Figure 16 to obtain the same final temperature. The uniformity of the temperature during a windtunnel test can be seen in Figure 18 which shows the temperature measured by the thermocouple on the top layer of pebbles and that measured by the aspirated plenum probe.

The platinum-rhodium thermocouple imbedded in the top layer of pebbles has proved to be a simple and reliable method of monitoring the maximum pebble temperature. A heavy 1" diameter alumina protection tube surrounds the couple which can be replaced readily if it fails. An optical pyrometer sighting downwards through the flame detector window was found to be less suitable because of the low effective emissivity. Taking the thermocouple reading as the true temperature of the surface, an emissivity of 0.24 was calculated at 2900°R.

Platinum-rhodium thermocouples introduced through the base flange of the heater and positioned at various levels have survived for

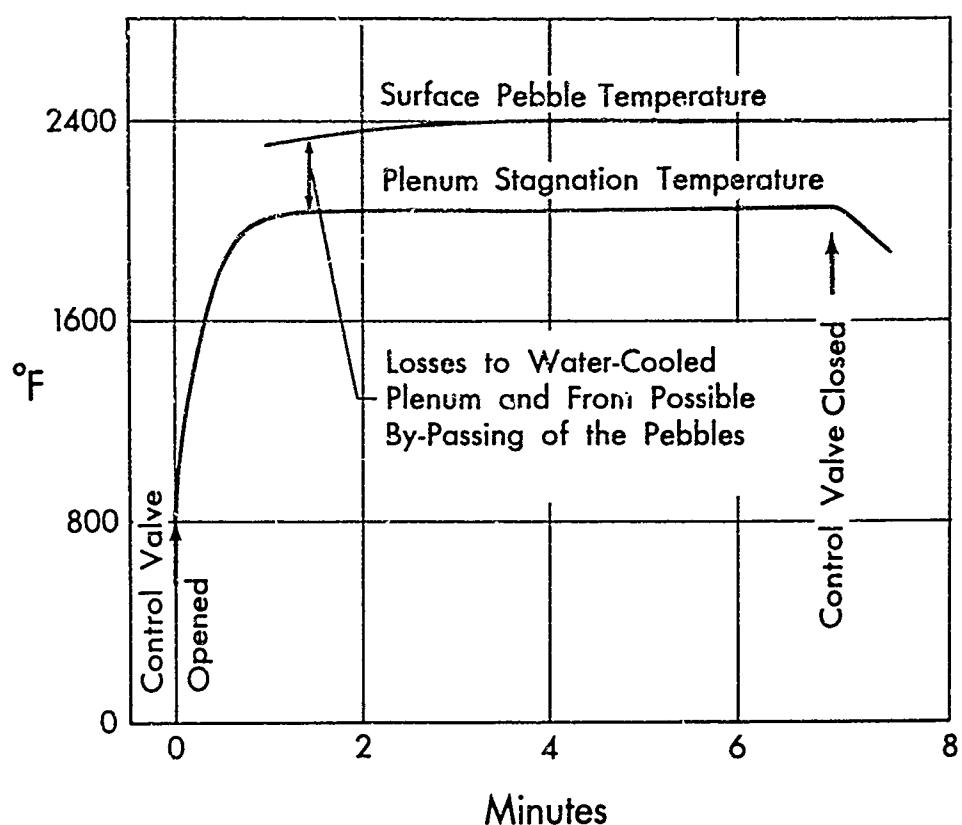


Fig. 18. Temperatures measured during windtunnel operation.

a maximum of seven cycles after installation. Several types of installation have been tried, ranging from bare 0.20" diameter wire in small alumina beads to 0.40" wire in heavy alumina protection tubes. The use of these thermocouples has been abandoned now that the firing characteristics are adequately known. Two Chromel-Alumel "megopak" thermocouples have been continuously used to measure the temperature in the pebbles 3" and 6" above the grate. They can be withdrawn from inconel protection tubes and replaced readily. In this region, the temperature of the pebbles is kept below 2300°F.

Chromel-Alumel thermocouples distributed over the outside of the pressure vessel initially indicated less than 200°F. A radiation shield of sheet aluminum was then attached around the vessel,  $\frac{1}{2}$ " away from the outside surface, which successfully raised the surface temperature to between 220°F and 350°F. This was necessary to eliminate the possibility of water condensation inside the heater during the firing cycle.

(3) Reliability and Maintenance. Only one structural problem has occurred. The internally-cooled shelf supporting the arch brick developed leakage through a fractured weld. The effect was a gross deterioration in the windtunnel dew point and a repair was necessary. The weld was repaired, supporting gussets were added under the shelf to enable air-cooled operation in the event of a recurrence of leakage, and thermocouples were installed to monitor the shelf and gussett temperatures. A small leak subsequently developed and the shelf is now operated using air-cooling to maintain surface temperatures below 800°F.

It was observed during the above repair work that aluminizing

of the inside of the pressure vessel had prevented any deterioration of the metal surfaces.

b. Windtunnel Operation

The windtunnel was operated initially with the  $M = 2.5$  nozzle for a total of 14 tests before the  $M = 4.5$  nozzle became available. These tests were used to try out procedures, instrumentation and controls and to locate any hot spots in the components. Some modification was also made in the initial section of the plenum (Figure 14), but the nozzle itself was not calibrated. Subsequent tests have used the Mach 4.5 nozzle, which was required for the first series of combustion experiments.

(1) Controls. The electric-pneumatic control loop has been entirely satisfactory and reliable. The stagnation pressure is repeatable to a fraction of a percent and is entirely constant following the starting transient of less than a minute up to the point at which the control valve is fully open. The useful testing time is limited by the capacity of the air storage and varies between five and eight minutes depending on the stagnation temperature.

(2) Stream Purity. The air leaving the heater contains some impurity. Water vapour is picked up in the pebble bed since the measured dew point of the air in the plenum is consistently higher than that of the supply air. Typically the supply air has a dew point of  $-38^{\circ}\text{F}$  to  $-40^{\circ}\text{F}$ , while the plenum dew point decreases during a test to a minimum value between  $-15^{\circ}\text{F}$  and  $-25^{\circ}\text{F}$ . Careful procedures are used following the firing cycle to eliminate water from the pressure vessel and piping, but improvement on the above figures has not so far been

possible. For the present combustion experiments, the dew point is constantly recorded during a test as one of the test conditions.

A procedure has been adopted of blowing through the pebble bed to atmosphere for some 15 seconds before attaching the windtunnel to the outlet flange. In this way, alumina dust from the pebbles produced during firing is blown out rather than through the nozzle. However, the continued presence of dust particles in the stream is evidenced by the roughness of surfaces exposed to the flow. No extra precautions have been taken since the rate of deterioration is tolerable and the effects of alumina particles on the combustion measurements being made is considered small.

(3) Nozzle Calibration. The nominal Mach 4.5 nozzle has been partially calibrated over a limited range of stagnation conditions using a seven tube impact pressure rake and a traversing impact pressure probe. The results show the Mach number to be higher than was designed for, although the precise value is uncertain because of vibrational relaxation effects. Figure 19 shows the results of impact pressure surveys near the nozzle exit plane reduced on the basis of frozen flow.

It is likely that the vibrational excitation at the elevated stagnation temperatures does not follow an equilibrium path during the expansion in the nozzle. The "freezing point" criterion given in Reference 1 predicts frozen vibrational excitation, upstream of the throat at the design stagnation temperature and pressure ( $3000^{\circ}\text{R}$  and 300 psi). Consequently, the flow in the nozzle more nearly approximates a frozen flow expansion. The design inviscid area ratio of 20.0 which would give a Mach number of 4.5 at  $3000^{\circ}\text{R}$  if the expansion were in equilibrium, gives

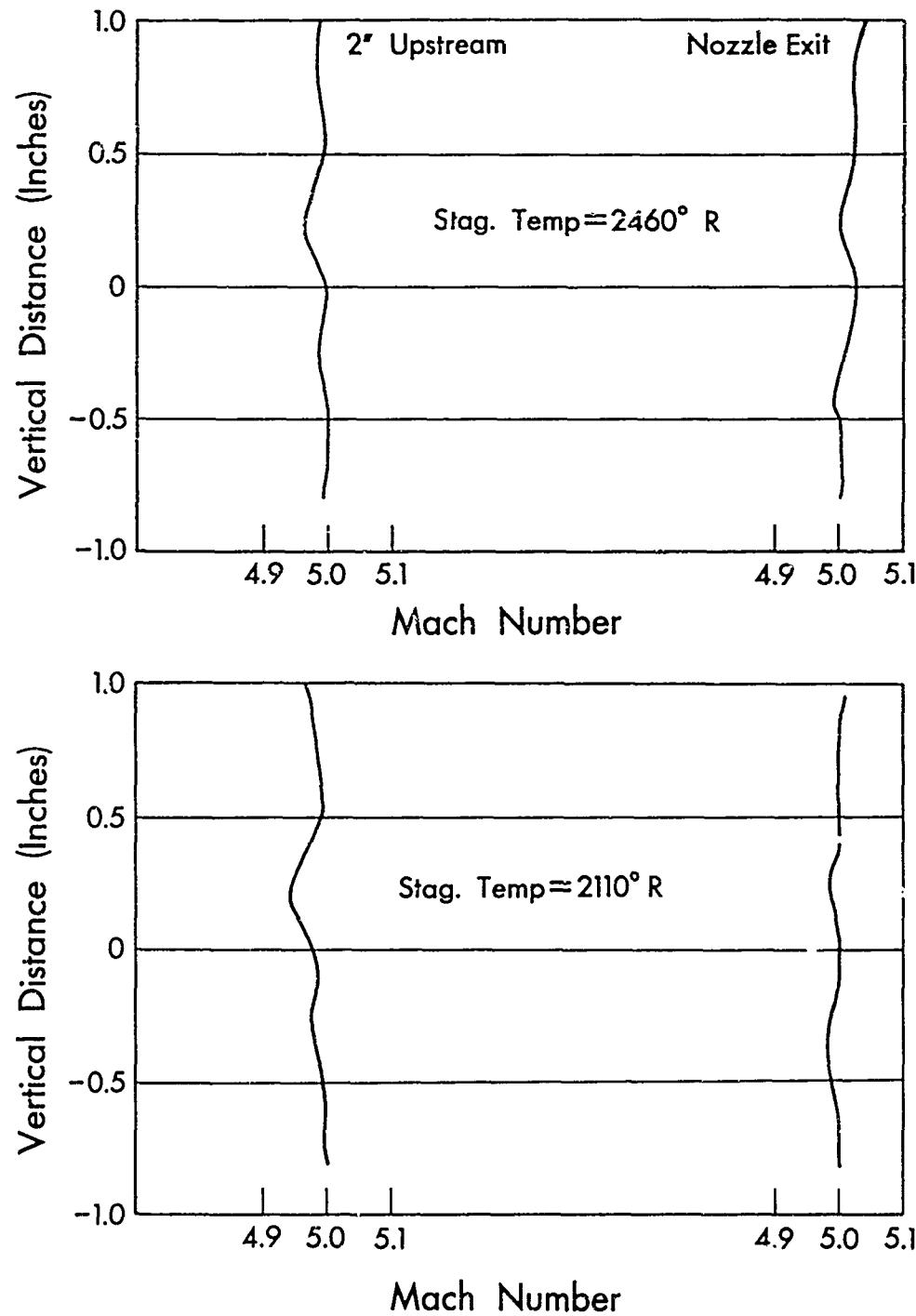


Fig. 19. Mach number distribution in the vertical centerplane near the exit of the nozzle.

a frozen flow Mach number of 4.75. Since the measured Mach number is higher yet, a check was made on the boundary layer correction.

A 1/32" diameter flattened impact pressure probe was inserted through a static pressure tap in a contoured wall of the nozzle, 16" downstream of the throat, and was held in a traversing mechanism which gave 0.6" of movement normal to the wall. Using the measured impact pressure distribution and the static pressure measured by the same pressure tap when the probe was removed, a distribution of Mach number near the wall was obtained. Assuming perfect gas behaviour, the displacement thickness is given by

$$\delta^* = \int_0^\infty \left(1 - \frac{T}{T} \frac{M}{M_\infty}\right) dy,$$

where  $\infty$  refers to free stream values. For the test considered,  $T^\infty$  was 485°R and the wall temperature near 530°R which implies that  $\frac{T}{T}$  varies through the boundary from just less than unity to just greater than unity. Hence, approximately,  $\delta^* = \int_0^\infty \left(1 - \frac{M}{M_\infty}\right) dy$ . Evaluating  $\delta^*$  for the measurements shown in Figure 20, a value of 0.10" is obtained, whereas the design value at this station was 0.16". Thus, the method of Reference 8 has overestimated the boundary layer growth and furthermore the effects of this error are magnified when the growth along the side-walls is allowed for along the contoured wall. Thus, it appears that the inaccuracies in the inviscid contour and the boundary layer growth computations are additive. The measured Mach number profiles are flat to within 0.5% over the two-inch core which has so far been surveyed, however the nominal Mach number of the nozzle is 5.0.

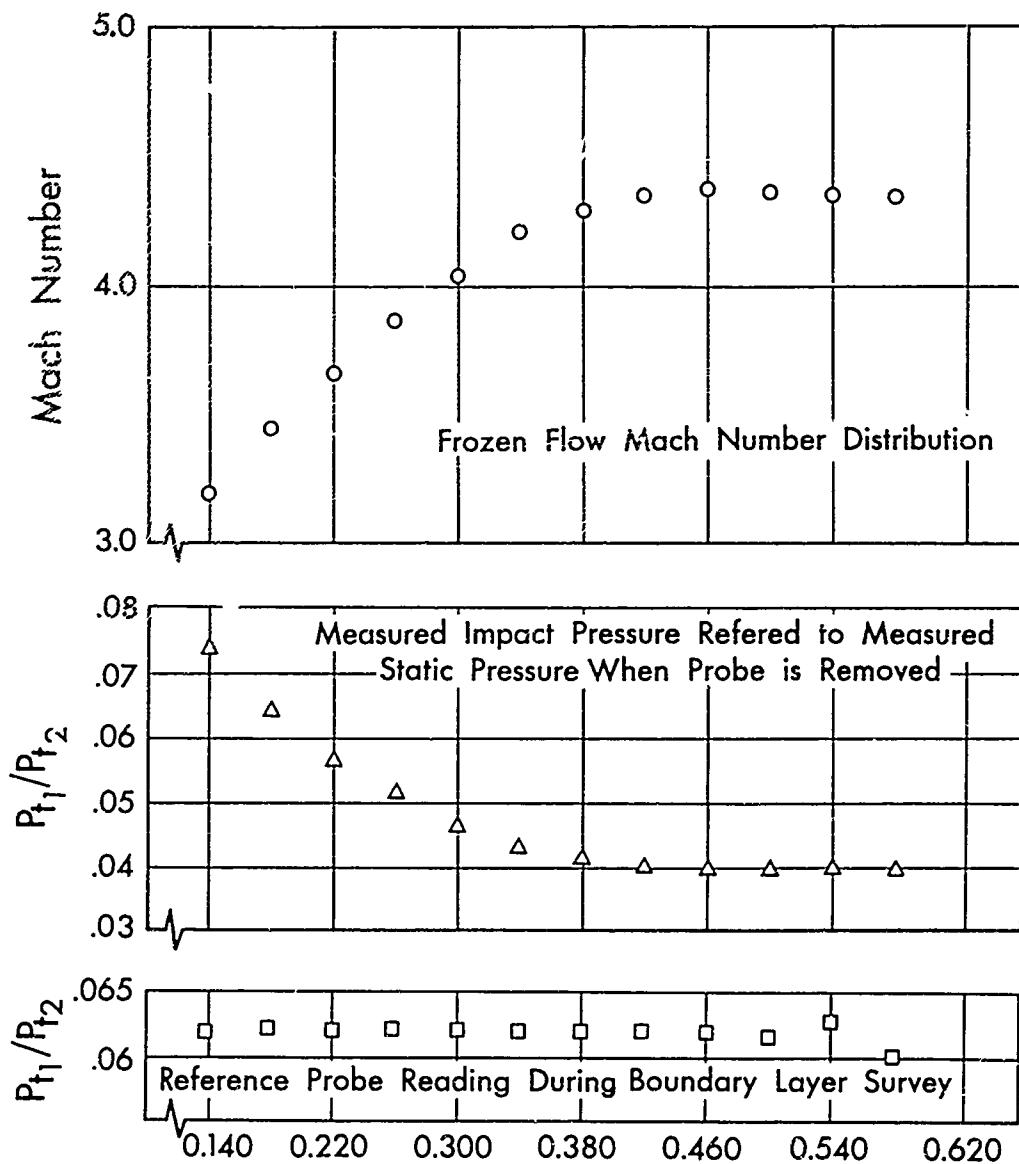


Fig. 20. Impact pressure measurements through the boundary layer on the contoured wall of the nozzle.

Early evidence of the higher Mach number was the difficulty of starting the flow. Starting pressures with an empty tunnel are typically about 285 psia, and over 300 psi with a probe installed.

#### Optics

Quartz windows have been used and have successfully withstood the pressure, temperature and heat shock loads. However, the quality of the schlieren photos obtained deteriorated rapidly as a result of pitting and staining of the inside surfaces of the windows. The rate of pitting, which is a result of alumina dust carried by the air flow, was reduced by the method of operation outlined above. The staining was eliminated by avoiding the use of gasket compounds which could be sucked into the flow and burn over the windows, and by revising the method of mounting the quartz in the window frames to eliminate the use of potting compounds. The old and revised window mounts are shown in Figure 21. The new mount has two advantages. It uses standard optical blanks which can be readily removed for repolishing and it positively locates the inner quartz surface flush with the tunnel wall. The grinding of the circumferential groove for the retaining ring was not a problem, although it was found necessary to relieve the sharp edges to avoid splintering.

A typical shadowgraph of the Mach interaction produced by wedge shocks is shown in Figure 22.

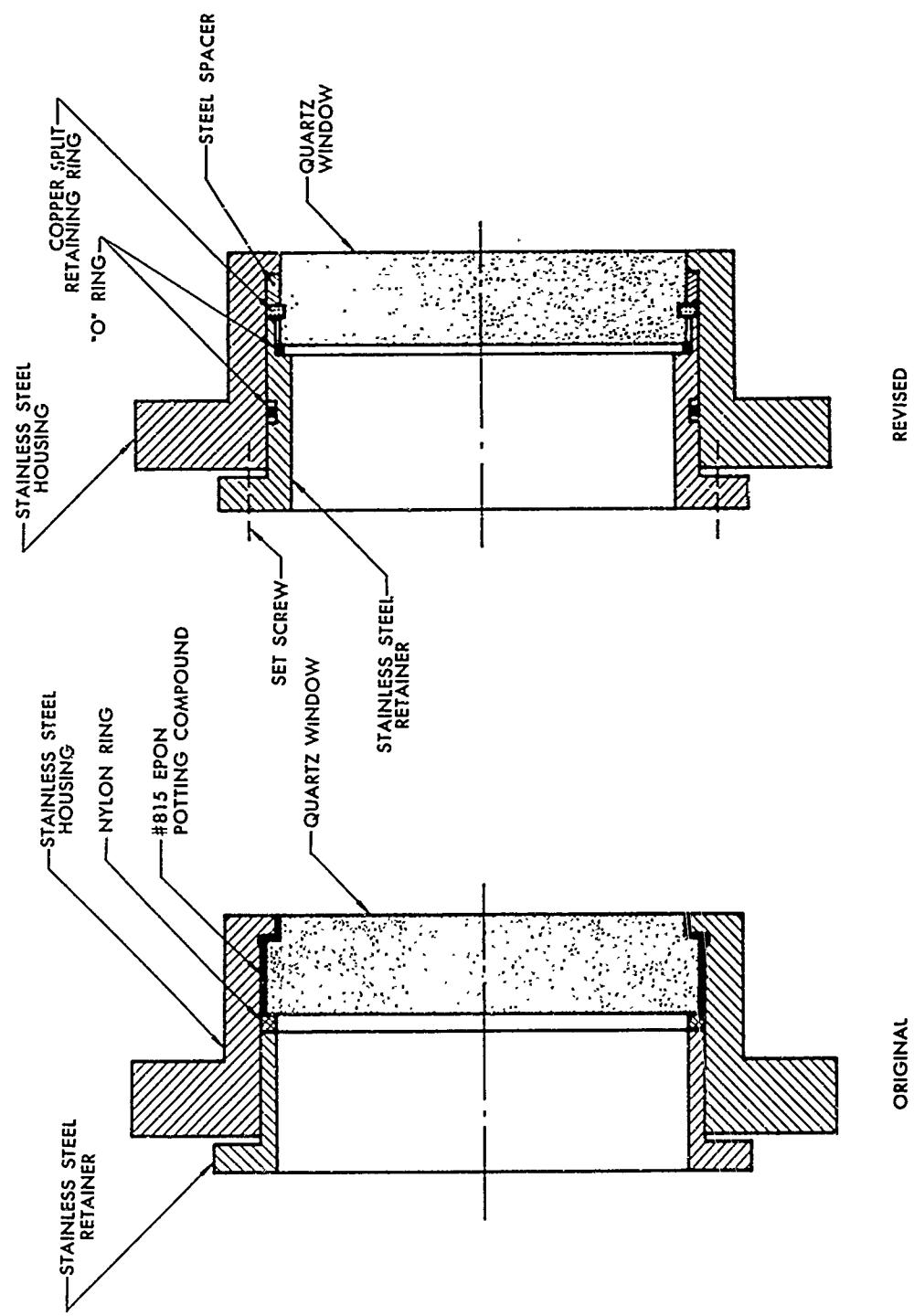


Fig. 21. Original and revised window mounts.

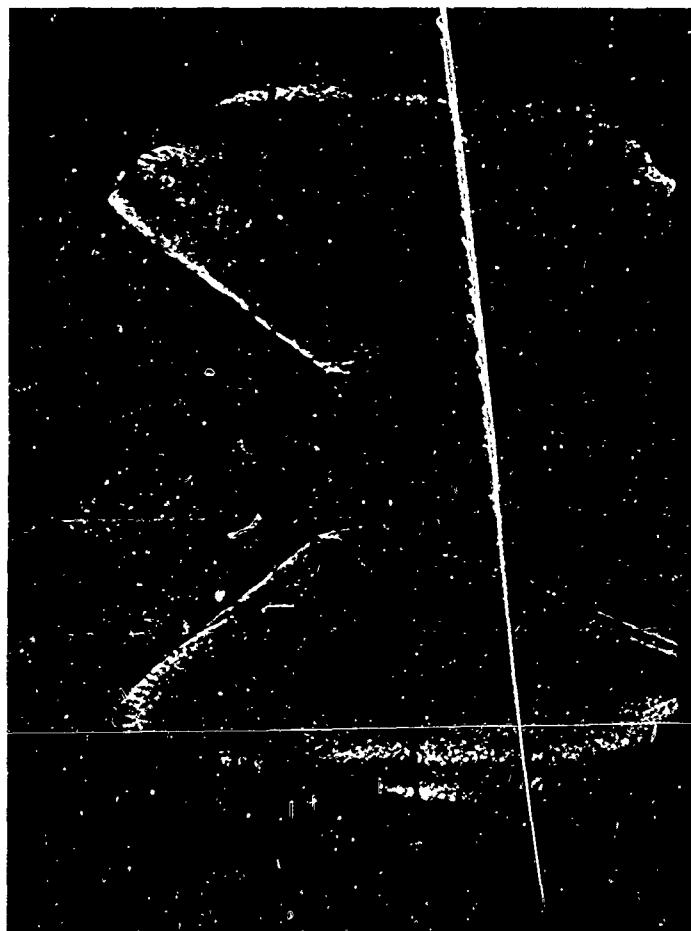


Fig. 22. Spark shadowgraph of wedge-generated Mach intersection at  
 $M \approx 5.0$ .

#### 4. CONCLUDING COMMENTS

The facility described above has been in consistent operation for more than two years and is currently being used for experiments in shock induced combustion. The following comments can be made in summary:

(1) The natural gas heated pebble bed has proved to be an extremely reliable piece of equipment. The interlocked controls have enabled unattended overnight firing cycles to be used and a single platinum-rhodium thermocouple, resting on the pebbles, has provided reliable measurements of the firing temperature. The internally-cooled shelf supporting the arch brick has been operated successfully with air as the coolant. Initial operation with water cooling resulted in fractured welds. Tunnel stagnation temperatures up to 2800°R are readily repeatable and stagnation pressures are automatically controlled to within a fraction of a percent.

(2) Duration of operation is limited solely by the air storage capacity and varies between 5 and 8 minutes depending upon temperature.

(3) Good shadowgraph and schlieren photographs have been obtained in a difficult environment. Impact pressure, static pressures, and recently stagnation temperature surveys have been obtained.

(4) The flow at the exit of the present nozzle is uniform in the vertical plane to within 0.05 of Mach 5.0 based on "frozen" flow from 2000°F and 350 psi. The discrepancy between this and the design Mach number is a result of using an equilibrium flow method of characteristics for the inviscid design and an overestimated boundary layer growth obtained using Reference 8.

(5) Dust particles are present in the tunnel air flow, most of which are, judging from a microscopic evaluation of an exposed surface, less than 100 microns size. These do not interfere seriously with the present combustion experiments, but would have to be taken into account in considering other types of experiments.

ACKNOWLEDGMENT

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Of the many people concerned with planning, designing and purchasing for the facility, the following deserve mention: Yoshio Aoki was largely responsible for the initial specifications, David L. Dunn and the Boeing Wind Tunnel Design group designed and supervised the manufacture of the windtunnel components. Robert Flanagan and his mechanical design group at BSRL were responsible for the design of the air supply system, the pebble bed heater, plenum and exhaust system, and arranged for the complete installation. John Culton has been an invaluable technician since the installation began, and the continuing support of the BSRL facilities group and machine laboratory is also gratefully acknowledged.

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